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Experimental Study on the Radiant Cooling Load of Floor Based on the Radiant Time Series Method

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Abstract

A calculation method about the radiant cooling load of floor which is based on radiant time series (RTS) method is presented: With the use of radiant time factors, radiant cooling load can be easily calculated from the radiant heat gain. Based on experimental data of total heat gain and total cooling loads collected within 24-hours, radiant heat gain of floor can be calculated through convection and radiation separating method, using PRF/RTF Generator software to calculate the radiant time factor of floor; the radiant cooling load of floor is calculated and compared with the measured values. The results for the 5 experimental conditions show that the radiant cooling load of floor peak error is less than 2.3% comparing with the value which is calculated by radiant time series method, and average error is not more than 3.2%. Its mean absolute error is 1.2% and 1.7% respectively. The experimental study indicated that convection and radiation separating method on wall could calculate the radiant cooling load of floor.

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Keywords: Radiant heat gain; Radiant cooling load of floor; Radiant time factors

1. Introduction

The radiant time series (RTS) method [1,2] is a new method for performing design cooling load calculations, which was recommended by ASHRAE TC4.1(the design load calculations technical committee). In this method the heat gain of the room is divided into two parts: convection heat and radiation heat. Convection part directly becomes the cooling load. As for radiant heat gain in a room, radiant cooling load is calculated by using a 24-term radiant

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time factors (RTF), which provides huge significance of avoiding iterative calculation as in the transfer function method [3,4]. Radiant time factors of building envelope should be present to calculate radiant cooling load in radiant time series method. There are two kinds of radiant time factors calculation: one is based on the heat balance method and there is a calculation software existed [5,6]. The other one is the database of transfer function established by ASHRAE [7,8,9], through extracting transfer function coefficients according to the building envelope material properties and then the radiant time factor is obtained by matrix operations. The radiant time factor calculated in the two methods is for the whole enclosed room envelope, thus the radiant load calculations is also for the whole room. If you make use of software to calculate, you can get the solar radiant time factor of indoor floor, it is also called the radiant time factor of floor.

The paper presented a calculation method of the radiant cooling load of floor, which is based on radiant time series method. By using PRF/RTF Generator software to calculate the radiant time factors of room floor, we can calculate the radiant load according to the radiant heat gain of floor, and then compared it with the measured values. The study on its change trend with the change of wall heat flow and air volume, research results will provide a new thought for the application of radiant time series method in the calculation of radiant cooling load of floor. Then it provides direction for the calculation method of radiant transfer from non-air conditioning area to air conditioning area in large space.

Nomenclature

q_τ	radiant load at time τ, W
$Q_{\tau\text{-}n\Delta\tau}$	the part of the heat gain radiant at time n, W
r_n	the radiant time factor at time n
q	Radiant hourly load column vector
Q	Radiant hourly heat gain column vector
R	irradiant time factor vector
$Q_{ii\lambda}$	thermal heat, W
Q_{id}	convection heat, W
Q_{iR}	radiant heat, W
ε_i	wall emissivity
A_i	wall area, m^2
σ	blackbody radiant constant, $5.67\times10^{-8}W/(m^2\cdot K^4)$
θ_i	wall temperature, K
J_i	effective wall radiant W/m^2
X_{ij}	angular coefficient

2. Methods

2.1. Principles of radiant time series methods

When radiant time series method is used to calculate the radiant load, radiant load at time τ is related to radiant heat gain at time τ and its previous time steps, using the radiant time factors in the corresponding time to reflect the effects of radiant load at time τ. In time radiant series method, radiant hourly load can be obtained through:

$$q_\tau = r_1 Q_\tau + r_2 Q_{\tau-\Delta\tau} + r_3 Q_{\tau-2\Delta\tau} + \cdots + r_{24} Q_{\tau-23\Delta\tau} \tag{1}$$

For the entire period, radiant load can be written in matrix format:

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ \vdots \\ q_{24} \end{bmatrix} = \begin{bmatrix} r_1 & r_{24} & r_{23} & \cdots & r_2 \\ r_2 & r_1 & r_{24} & \cdots & r_3 \\ r_3 & r_2 & r_1 & \cdots & r_4 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ r_{24} & r_{23} & r_{22} & \cdots & r_1 \end{bmatrix} \times \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ \vdots \\ Q_{24} \end{bmatrix} \quad (2)$$

The matrix can be abbreviated as follows:

$$q = RQ \quad (3)$$

This paper makes the radiant time factors of floor as shown in Fig.1, by the PRF/RTF Generator software depending the laboratory related structure and thermal information.

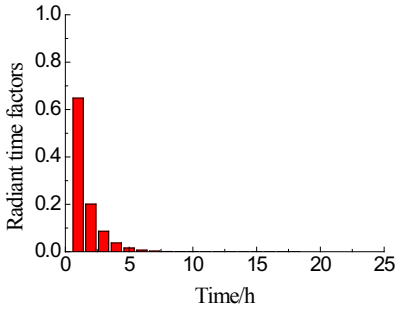

Fig.1. Laboratory solar radiant time factor of floor

2.2. Experiment mechanism of radiant cooling load of floor

A heat conduction, convection and radiation transfer process occurs simultaneously in the building internal wall surface. Using the separation method of convection and radiation on the wall, the inner wall surface heat balance is expressed as in Equation (4) as:

$$Q_{i\lambda} + Q_{id} + Q_{iR} = 0 \quad (4)$$

The radiant heat Q_{iR} can be calculated by effective radiant model by using the wall temperature, angular coefficient and wall emissivity to get ground active radiant coefficient, then column matrix to solve the wall radiation heat as follow Eq.5 and 6 [10]:

$$Q_{iR} = \frac{\varepsilon_i A_i}{1-\varepsilon_i}\left(\sigma\theta_i^4 - J_i\right) \quad (5)$$

$$J_i - \left(1-\varepsilon_i\right)\sum_{j=1}^{n} J_j X_{ij} = \varepsilon_i \sigma\theta_i^4 \quad (6)$$

In the experiment, simulating wall thermal heat by using electric film to disseminate heat. Its heat flux can be measured by instrument; the amount of radiant heat transferred by the wall is calculated by the Eq.5 and Eq.6; and then Eq.4 can be used to calculate wall convection heat. In the experiment, The amount of radiant heat is net radiant heat of every wall, in addition to the heated surface, which is also equal to the net radiant heating surface heat loss; rooms radiant load refers to the sum of separated convection heat from other walls except the heated surface,

through convection radiation separation method, which is called separated cooling load. For the floor, radiant floor heat gain of floor is the net radiation heat of floor; radiant cooling load of floor is the convection heat that is separated out by convection radiation separation method.

2.3. Laboratory configuration and test plan

Experimental system principle is shown in Fig. 2. It consists of a chamber, cold and heat source, air handling system, electrical control and test system etc. The experiment was taken in an environmental chamber (2.5m×2.1m×2.5m, and 100mm polyurethane insulation board). The environmental chamber is located in a room with constant temperature, and the surrounding environmental temperature can be controlled. Fig.3 shows experimental arrangement of temperature and heat flow measuring points. We can see that the air temperature is tested by 4 measuring lines and each has 2 measuring points, respectively. Room temperature is described by the mean temperature of 8 measuring points. There are 2 points and 1 point in the non-heated surface to test wall temperature and heat flow respectively, north wall of heated surface has 4 points and 2 points, respectively. Each measured value of wall temperature and heat flow is described by arranged points or its mean value.

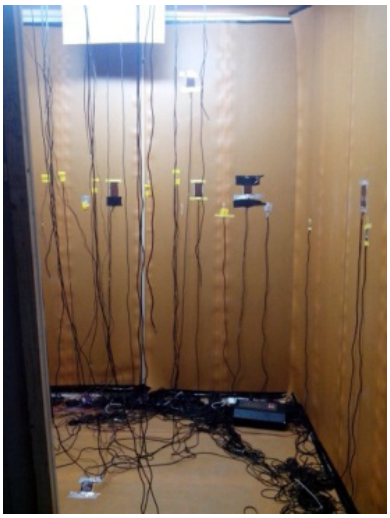

Fig.2. Inner scene of chamber in experiment.

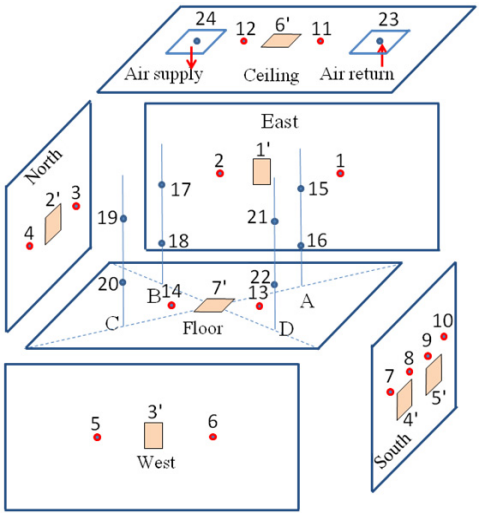

Fig.3. Testing points layout of temperature and heat flux.

In experiment, air temperature, supply and return air temperature, and wall temperature are tested by temperature sensor, the wall heat flow is tested by heat flow sensor, and both of them are collected by JTNT-C. The supply and return air volume flow rate are tested by air flow meter. Before experiment, a laboratory calibration for each test instrument was carried out. To simulate periodic heat flow of unsteady experimental conditions, inner surface electro-thermal films were operated by periodic methods. The heating power is set as periodic curves, as shown in Eq.7, and experimental conditions in detail are as Tab.1. In these experiments, indoor temperature is kept constantly at 25.5°C, and the period of experiment is 24h (to get the analytical data), which is the last 24h period of a 42h experiment.

$$P = a\left(\sin\frac{2\pi}{1440}t + b\right) \tag{7}$$

Table 1. Description of experiment condition.

Case	a	b	Heating power average/W	Heating power amplitude/W	Air volume/$m^3 \cdot h^{-1}$
1	360	1.5	540	360	501
2	300	1.5	450	300	501
3	110	2.18	240	110	501
4	300	1.5	450	300	335
5	300	1.5	450	300	662

3. Results

Radiant heat gain translates into radiant load, and finally transformed into radiant cooling load, which is separated load. Convection heat of all inner surfaces is equivalent to total cooling load of supply air and return air. In the experiment, air conditioning load is required through the measured data of supply air and return air, while separating cooling load is gained through convection and radiation separating method. In the condition of case 1, air conditioning load and separating cooling load of room are shown in the Fig.4. From the figure, air conditioning load and separating cooling load is observed to change periodically, which is because heat flux of the south wall surface changes periodically.

24-term floor radiant time factors of floor resulted from PRF/RTF Generator software, with the wall temperature tested hourly and Eq.5 and Eq.6, we can calculate the radiant heat gain of floor. With the 24-term radiant cooling load of floor obtained by matrix (2), it is the RTS calculated load of floor, which should be equal to separated convection term from radiation and convection of floor surface. In the condition of case 1, radiant heat gain of floor, the measured load and calculating load of RTS are shown in the Fig.5. From the figure, along with the time, radiant heat gain of floor firstly increases, and then decreases, which is the same as radiant cooling load floor. Among the time, heat gain is slightly more than load in the first half time, slightly less than in the last half time, which indicates radiant load shows decline and in the peak compared with radiant heat gain, but delay is not significant.

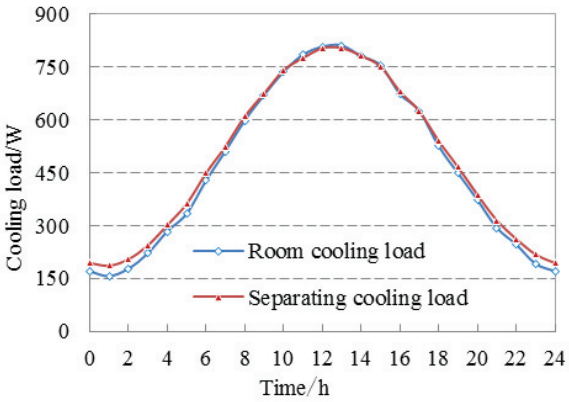

Fig.4. Case1verification of separated load of room.

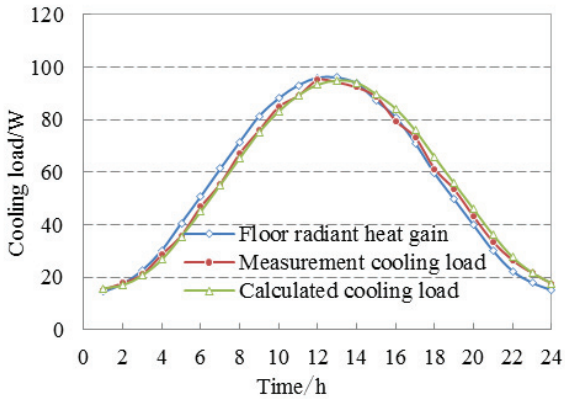

Fig.5. Radiant heat gain and radiant load of floor

4. Discussion

For 5 experiment conditions, air conditioning cooling load of room is relatively close to the separated cooling load, there is an error analysis in Tab. 2. In general, the peak error of each condition is less than 4.7%, and the mean error is not more than 6.1%. We know that when ventilation rate keeps constant (case1, case2, case3), the wall heat flow decreases gradually. It is suggested that both the air conditioning cooling load and separated cooling load of

room decreased. When wall heat flow keeps constant (case2, case4, case5), the ventilation rate increases gradually. It is concluded that both the air conditioning cooling load and separated cooling load of room decreased.

Table 2. Analysis of cooling load error of room.

Conditions	Peak AC load/W	Peak separated load/W	Peak error/%	Mean error//%
case1	811	803	-1.0	2.5
case2	679	665	-2.1	0.9
case3	307	321	4.7	6.1
case4	707	684	-3.2	0.5
case5	660	673	2.0	5.4

The error between RTS calculated radiant cooling load and measured radiant cooling load of floor is shown in Tab.3. From Tab.3, we can see the peak and mean value of measured value and calculated value of RTS is nearly the same (in terms of the 5 cases), and the maximum error is 2.3%, and 3.2%, respectively. As shown in Fig.5, the radiant cooling loads of floor lagging are behind the floor radiant heat gain of floor, but little time lag. This is mainly because the laboratory has good insulation, heat storage properties was not significant. In term of variable heat flux constant air volume (case 1, case 2, case 3), and constant heat flux variable air volume (case 2, case 4, case 5), the larger of the former heat flow, the greater of the peak load; the larger of the latter air volume, the lower of the peak load. In total, even if there is different heat flow in the heat surface or different air volume indoor, the calculated load is still nearly in line with the measured value. That is to say, radiant time factors have nothing to do with the operation conditions, and it is just related to the building structure and thermal properties.

Table 3. Error analysis between calculated load of RTS and measured value of floor.

Conditions	Peak and error			Mean and error		
	Measured value/W	RTS value/W	Error/%	Measured value/W	RTS value/W	Error/%
case1	95.1	94.9	-0.2	54.9	55.5	1.0
case2	80.9	82.0	1.4	46.6	47.6	2.2
case3	34.7	35.5	2.3	21.8	22.5	3.2
case4	90.6	89.1	-1.8	51.9	52.7	1.6
case5	77.5	77.6	0.2	45.0	45.2	0.4

5. Conclusions

(1)The paper presented a calculation method about the radiant cooling load of floor which is based on radiation time series method. The calculation method is feasible after experimental verification. Compared with the measured value, its peak and mean value of the difference comparing with the calculated value of floor is less than 2.3% and 3.2%, respectively. The average error of the 5 conditions is 1.2% and 1.7%, respectively.

(2)The experiment study result suggested that the convective heat separated from the radiation and convection of the inner surface without heat transfer can be described as radiant cooling load, according to the heat balance method. It is the sum of room cooling load and convective heat separated of room from the wall except for heat surface. In terms of room radiant load, the maximum peak and mean error is 4.7%, and 6.1%, respectively. The average error of the 5 conditions is 2.6% and 3.1%, respectively.

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